Characterization of the ExB Penning Discharge Using Electrostatic Probes

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Yevgeny Raitses,[1] Eduardo Rodriquez,[2] Valentin Skoutnev,[3] Andrew Powis,[4] Brian Kraus,[5] and Igor Kaganovich[6]
Princeton University Plasma Physics Laboratory, Princeton, New Jersey, 08543, USA

Andrei Smolyakov[7]
University of Saskatchewan, Saskatoon, Saskatchewan, S7N 5E2, Canada

Abstract: In this paper, we highlight results of resent studies of ExB Penning discharge in which electrostatic probes were used for time-resolving measurements of the plasma potential and the electron energy distribution function (EEDF) [1,2]. For measurements of the plasma potential, a floating emissive probe is used [1,3]. Oscillations of the plasma density are deduced from measurements using an ion probe [1] and measurements of the EEDF using a fast sweeping Langmuir probe (~50-100 kHz) [2]. From plasma potential and density measurements, the anomalous electron cross-field current due to spoke oscillations were deduced and compared with the discharge current and predictions from simulations [4]. A key result is that the anomalous cross-field current induced by low frequency oscillations conducts a large (up to 100%) fraction of the discharge current in the Penning discharge

I. Introduction

Magnetized plasmas in cross-field discharge devices exhibit complex nonlinear behavior resulting in variety of turbulent fluctuations and structures that critically affect operation and performance of these devices. E×B rotating structures or so-called rotating spoke oscillations have been observed in a variety of laboratory and applied plasma devices with magnetized electrons and non-magnetized or weakly magnetized ions such as linear plasma devices, Hall thrusters, Penning discharges, sputtering magnetrons, applied field plasma source. These oscillations are usually low mode number with a characteristic frequency of $\Omega_{ce} << \omega \leq \Omega_{ci}$, where Ω_{ce} and Ω_{ci} are gyrofrequency of electrons and ions, respectively. Recent experiments of Hall thrusters and Penning discharges demonstrated that low frequency (1-10's kHz) spoke oscillations are responsible for anomalous electron cross-field transport. For the Hall thrusters, electron cross-field transport is of practical importance because it diminishes the thruster efficiency, which is the ratio of the plasma jet power to the input electric power. If the electric field decreases with the cross-field transport, it can cause plume divergence and thruster wall erosion. Our measurements in cylindrical Hall thruster (CHT) (Fig. 1a) and, more recently, Penning discharge (Fig. 1b)

[1] Principal Research Physicist, Plasma Science and Technology Department, yraitses@pppl.gov
[2] Graduate student, PPPL, Department of Astrophysical Sciences, Princeton University
[3] Graduate student, PPPL, Department of Astrophysical Sciences, Princeton University
[4] Graduate student, PPPL, Department of Mechanical and Aerospace Engineering, Princeton University
[5] Graduate student, PPPL, Department of Astrophysical Sciences, Princeton University
[6] Principal, Research Physicist, Theory Department, ikaganov@pppl.gov
[7] Professor, Physics Department, andrei.smolyakov@usask.ca

revealed a strong dependence of spoke oscillations on the input discharge parameters, including gas, gas pressure, the magnetic field, and the electron injection from the cathode [1,5,6]. Similar observations have been reported for conventional state-of-the art Hall thrusters [7].

The rotating spoke is a plasma non-uniformity that rotates usually in the $\boldsymbol{E} \times \boldsymbol{B}$ direction. The spoke can appear in different modes, but for, for example, CHTs, Penning discharge and cylindrical magnetrons, the most common is $m = 1$ mode (Fig. 3). In CHT and Penning discharge, the spoke was observed with a high-speed CCD camera and Langmuir probe measurements [1,5,6]. The spoke appeared on the camera as a spot of increased light emission that rotates in the azimuthal direction with the translation speed of an order of magnitude slower than the local E×B speed. On probes immersed in CHT and Penning plasmas, the spoke manifests itself through azimuthal oscillations of plasma potential, electron temperature and plasma density [1,2,6].

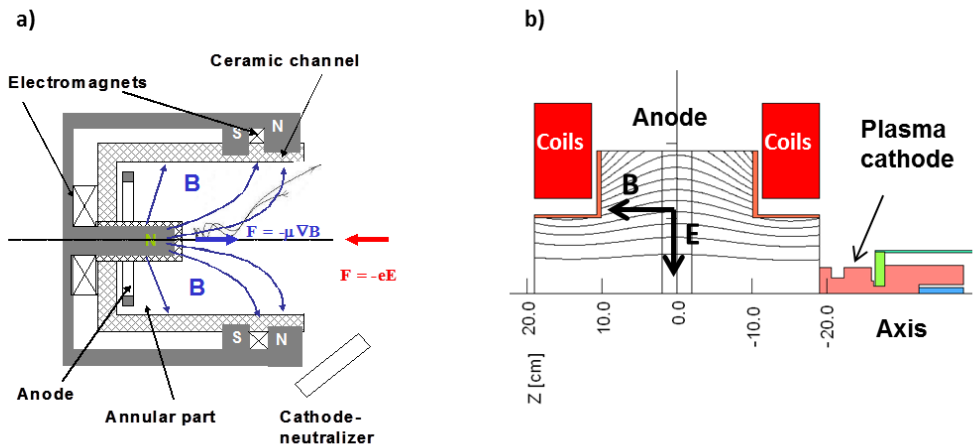

Fig. 1 Schematics of E×B configurations of the cylindrical Hall thruster [8,9] (a) and the Penning plasma discharge [1,3] (b).

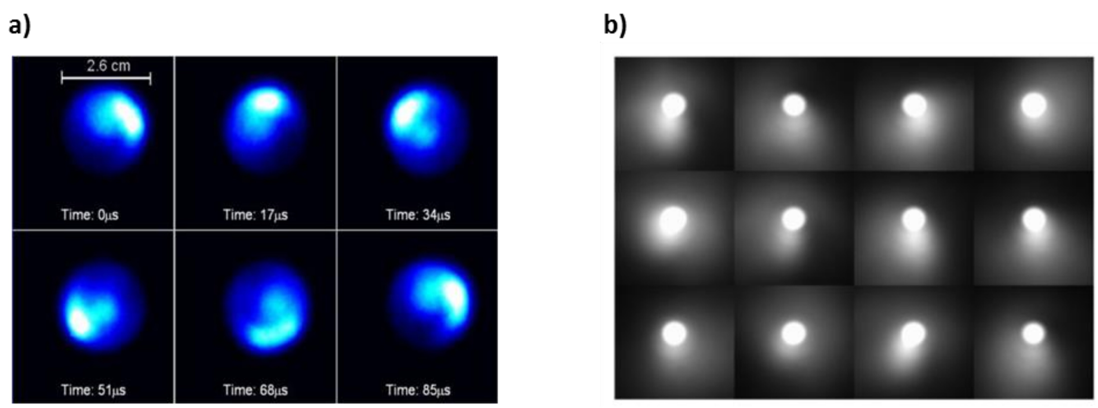

Fig. 3 E×B rotating spoke in CHT thruster [5] (a) and Penning discharge [10] (b)

Naturally, the spoke is a manifestation of one or coupled multiple instabilities of the cross-field plasma discharge. Our studies on Penning discharge provided new insights on the fundamental role of gradient drift (modified Simon-Hon type) instabilities driven by gradients of plasma density, temperature and magnetic field [11-13]. Ionization instabilities may be coupled to this electrostatic instability giving raise the formation of rotating plasma structures. We have identified in the experiment and simulations a strong connection between these plasma structures and electron transport. This connection is responsible for the mode transition, facility effects, and effects of the magnetic field, effects of device (e.g. thruster) geometry and materials on plasma structures. The overall physics picture, which we learned so far from our integrated experimental, simulations and theory efforts is as follows: small scale phenomena such as micro turbulence is responsible for anomalous transport, which determines both the electric field and pressure gradients, which in turn, can induce large scale gradient driven instabilities forming plasma strictures such as spoke. The dynamic of the plasma structure is also determined by a relatively slow rotation of ions due to a partial magnetization or momentum conservation, and charge exchange collisions.

In this conference paper, we briefly highlight results of probe diagnostic developments and applications which supported the above mentioned studies of the cross-field transport. References [1-3] provide detailed descriptions of the probe designs, results and analysis of probe measurements and their comparison with theory [11] and simulations [4, 14].

II. Experimental Setup

Our experiments were conducted primarily using the Penning discharge setup (Fig. 1b). This setup is built on a 10" diameter stainless steel 6-way cross vacuum chamber equipped with a pumping system consisting of a turbo-molecular and mechanical vacuum pumps. Most of experiments described in Refs. [1-3] (and highlighted here) were conducted using xenon gas at the operating pressure of 0.1-1 mtorr. The Penning setup is flexible and versatile with convenient access for various diagnostics and with well controlled parameters of the plasma. In operation, a dc voltage of 20-200 V is applied between the RF plasma cathode and the anode-chamber. The Penning discharge can be operated with uniform and non-uniform magnetic field by varying the directions of the currents in the electromagnet coils or by power coils with unequal currents. In all previous experiments, the Penning system was operated in a Helmholtz-like configuration with co-directed equal currents in both coils. Under the variations of the magnetic field of 30-500 Gauss, the Penning discharge system sustain an efficient ionization of Xenon with plasma properties comparable to the plasma properties in the near anode region of the Hall thrusters where strong rotating spoke oscillations are usually observed [15].

The Penning setup is equipped with a set of electrostatic probes placed on manually-controlled positioning stages. This allows to map plasma properties inside the plasma column. A negatively biased ion probe is used to deduce plasma density. The probe collects saturated current in the Bohm regime, without significant sheath expansion. The lack of expansion was experimentally resolved by observing collection current variations when changing probe negative bias; this gave changes below 5% per 10 V. A 10 kΩ shunt resistor was used to measure the current in the probe circuit.

A DC heated, floating emissive probe made from a 0.1 mm diameter thoriated tungsten wire is used to measure the plasma potential. The probe is operated in the regime of strong thermionic electron emission, manifested itself as the saturation of the hot-probe floating potential with respect to the ground. For the correct interpretation of this floating potential reading, the contribution from the heating voltage is taken into account as described in Refs. [1,3].

Floating potential of emitting surfaces in plasmas with respect to the space potential

Measurements of plasma potential are challenging, especially for complex, flowing, magnetized plasmas and collisional plasmas at elevated and high pressure, because such plasmas are subject to low and high frequency oscillations due to various instabilities. Emissive probes are commonly used for plasma potential measurements in such complex plasma environments. However, the interpretation of these measurements is not trivial [16]. Recent theories on sheaths near emitting walls have proposed a diversity of sheath topologies other than the commonly accepted space-charge limited (SCL) structure. In one case, an emitting sheath modelled in a particle-in-cell code showed oscillatory behavior [17]. Another theory poses a new steady-state potential structure, the inverse sheath, which can form in the limit of strong emission if ions gradually become trapped in the virtual cathode [18].

In recent experiments with different plasma sources, including RF cathode, Penning discharge and Hall thruster operating in a broad range of xenon gas pressure, we provided the evidence for two distinct sheath regimes, the SCL sheath and the inverse sheath [3]. A single probe filament was operated as a swept-biased probe to measure plasma potential or as an emissive probe to measure the floating potential (Fig.2). Comparison of the two measurements suggests a SCL sheath at low neutral pressures and an inverse sheath otherwise [3].

The above conclusions validate a model of ion trapping in the potential well in the SCL sheath (Fig. 3). For an inverse sheath to develop, charge-exchange ion buildup in a double layer or so-called virtual cathode near the emissive probe must dominate over trapped ion losses near the ceramic holder of the probe. If the gas pressure is above 0.1 mTorr, collisions are sufficiently frequent for trapped ions to neutralize the virtual cathode. In this case, the SCL sheath transitions to the inverse sheath regime. Lower neutral pressure or directed flows negate the possibility that slow ions will accumulate indefinitely, so that the only viable potential structure is an SCL sheath. Our experimental results agree with the conclusions of this model [3].

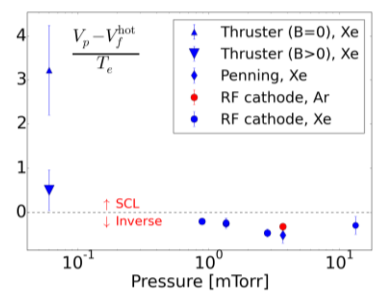

Fig. 2. Data from emissive probe and Langmuire probes in xenon plasma.

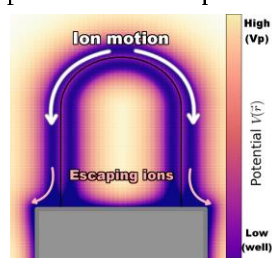

Fig. 3. Ion trapping at the emissive probe.

For the Penning experiments described in Refs. [1], we approximated that the floating potential of the emissive probe is equal to the space potential of the plasma. To assess how good is this approximation for the relevant operating regimes of the Penning setup, we tested what is the difference between the floating potential of the hot emissive probe and the plasma potential deduced from the I-V trace of the cold Langmuir probe. The difference did not exceed 5% [1]. Thus, our approximation was good enough for the sake of the analysis of transport properties in ExB Penning plasmas.

III. Recent Results of Measurements in the ExB Penning Discharge

A. Use of emissive and biased probes to characterize effects of the boundaries on the spoke

In recent experiments [1], the Penning setup was operated with two types of plasma boundaries (walls) terminating the magnetic field lines: dielectric and conductive (metal). Although the theory of Simon-Hoh instability and, more generally, gradient-drift instabilities, are limited to 2-D (along E-field and across B-field) considerations, our study of the boundary effect (along the B-field, i.e. the 3rd dimension) was aimed to check the prediction of the linear theory that for the Simon-Hoh instability to exist, it requires both electric field and the density gradient to be co-directed, across the magnetic field. By placing the metal wall biased to the anode potential, all magnetic field lines terminated at this wall should be equipotential, i.e. no electric field across the magnetic field shall exist in the plasma. Then, according to the theory of Simon-Hoh instability, in the absence of the electric field, the spoke instability should not develop.

As the first step towards validation of the short-circuit effect, we conducted two-dimensional (2-D) Particle-in-Cell (PIC) simulations. A detail description of the PIC code used in these simulations and results of PIC simulations for the Penning discharge can be found elsewhere [4,14]. In the 2-D simulations, the plane perpendicular to the device axis (i.e., the azimuthal and radial directions) is numerically resolved using Cartesian coordinates. The simulation domain thus corresponds to the end view of the actual device, shown in Fig. 1(b).The goal of these simulations was to explore what would happen to the spoke if the electrons escape to the anode along the field lines. To do so, the magnetic field lines were inclined so they would intersect the anode surface. This 2-D situation should qualitatively imitate the short-circuit effect in three-dimesional space of the actual Penning device with the axial magnetic field intersecting metal walls at the anode potential. Fig. 4 compares simulations results for the "normal" Penning discharge with the axial magnetic field (in simulations domain, out of the page plan). The spoke disappears when electrons can escape to the anode along the field lines. This result is consistent with experimental results (Fig. 5) showing that the spoke oscillations are substantially suppressed for the metal wall boundary.

From emissive and ion probe measurements, the short-circuit effect of the conductive boundaries can also be seen on the electric field in the plasma across the magnetic field (Fig. 6). In particular, for the metal wall case, the measured changes of the plasma potential in the radial direction are much smaller and therefore, the radial electric field is smaller too as compared to the Penning discharge with dielectric walls.

Using the measured density and plasma potential gradients, we estimated the contribution of the anomalous current to the discharge current and the growth rates for the collisonless Simon-Hoh instability [11]. According to these estimations, it follows that for the dielectric wall, the ExB current is the main contributor to the total discharge current; indeed, measurements lie within agreement (i.e. relative value of 40-100%). Consistent with this result for the anomalous current, the gradients corresponding to the dielectric boundary case are lying in higher values of the growth rate suggesting unstable plasma [1]. In contrast to this case, the stability of the plasma with metal walls is improved. The anomalous current still exists and contributes to the discharge current probably through higher frequency oscillations, which were also observed [1], and short-circuit effects. According to Ref. [1], in contrast to the dielectric wall case for which the classical collisional transport is almost two orders of magnitude lower than the measured anomalous current, for the conductive boundary case, the classical transport would provide only 6 times smaller current than the measured discharge current. A detail description of these results and their analysis are provided in Ref. [1].

Finally, the most recent experimental results for the Penning discharge with the diverging magnetic field (Fig. 7) demonstrated a complex spoke behavior which appears and disappears depending on the magnetic field strength. This interesting behavior may imply the importance of the axial gradients (magnetic field, plasma density etc.) along the magnetic field on the ExB rotating spoke.

B. Time-resolving measurements with the fast (up to 100 kHz) sweeping probe station (FSPS)

In Ref. [2], we have demonstrated the implementation of a fast sweeping Langmuir probe system that uses fully insulated power amplifiers (including their power supplies) to allow for analog subtraction of reactive and probe currents and thus direct measurement of the plasma current in ExB plasmas. The probe system was shown to provide EEDF, density, plasma potential, and temperature measurements at sweeping frequencies up to 100 kHz to within 20% of measurements with a commercial probe station MFPA, a well-accepted probe system in the field capable of obtaining robust I-V traces at low sweeping frequencies of 1 kHz and below [19].

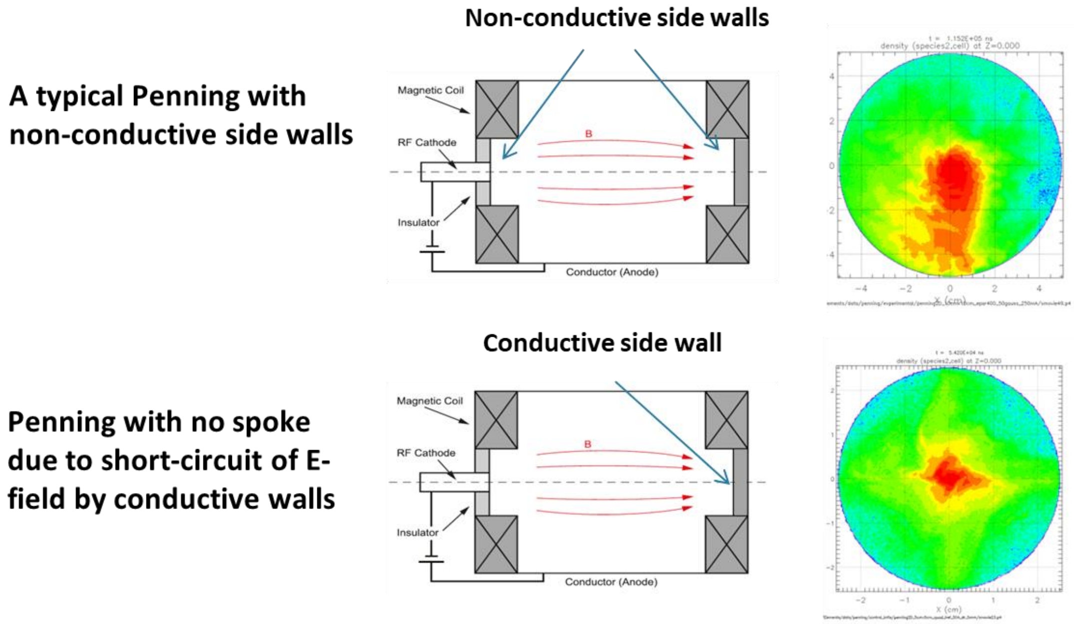

Fig. 4 Results of two-dimensional Particle-in-Cell simulations: Penning system configurations (left column) and ion density plots (right column). The top figure is for the 10 cm diameter Penning system <u>with non-conudctive insulating side walls.</u> The injection current is 250 mA and applied magnetic field is 50 gauss. Spoke frequency is 28 kHz. The bottom figure is for the 5 cm diameter Penning system with <u>conductive side walls</u>. The injection current is 250 mA and applied magnetic field is 100 gauss.

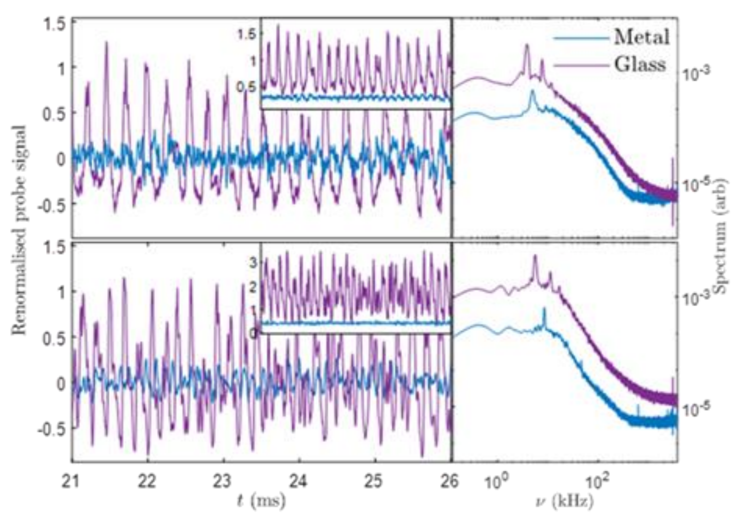

Fig. 5 Change in the spoke oscillatory behaviour of the plasma when changing the facing flange (Fig. 1b) from dielectric to conductive (metal). The top and bottom plots are for the magnetic of 30 Gauss and 150 Gauss, respectively. The plots of normalised ion probe signal $(n - \langle n \rangle)/\langle n \rangle$ are on the left, whle their correspong spectrum are shone on the right [1].

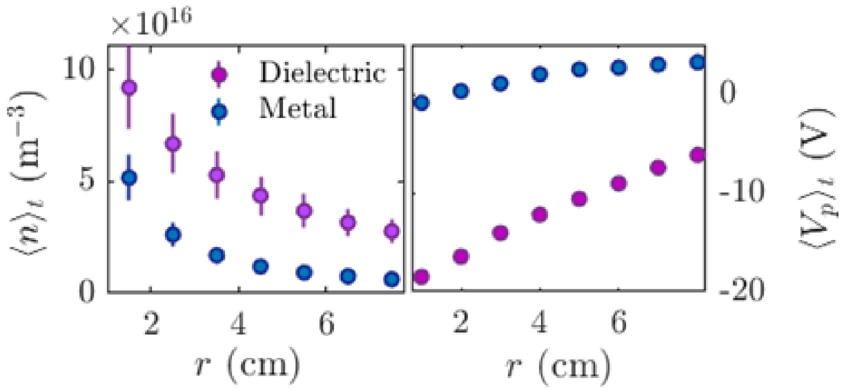

Fig. 6 Density and plasma potential profiles for B = 150G for both metallic and dielectric boundary cases

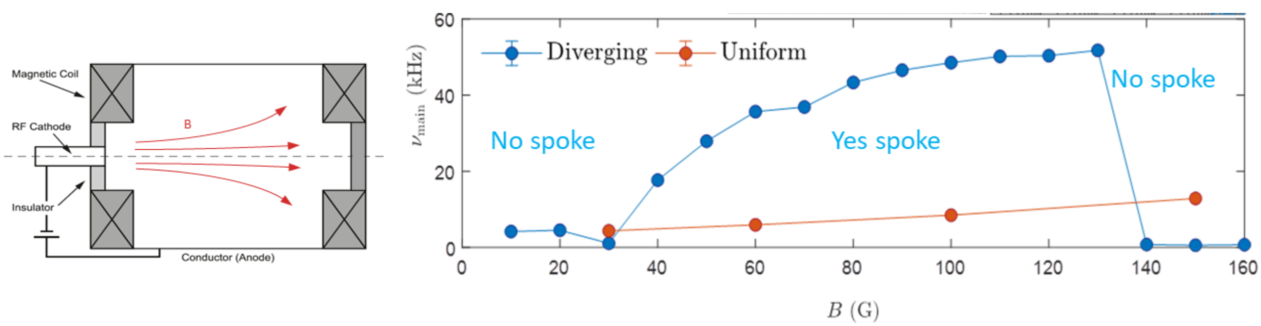

Fig. 7 The effect of the magnetic field topology on the spoke activity in the Penning system: the diverging magnetic field (left) and the comparison of the measured spoke frequency for the uniform and diverging magnetic field topologies

Fig. 8 compares results of the probe VI traces measured with our fast sweeping probe station and MFPA in the Penning discharge operated in a no-space regime, namely, elevated xenon pressure ~ 1.5 mtorr and low magnetic field ~ 30 Gauss.

In an application of the probe system to ExB plasmas with low frequency oscillations, we lowered xenon pressure to 0.1 mTorr and increased the magnetic field to 40 G magnetic field. These are experimental conditions for which the spoke is present and has a rotation frequency of approximately 4 kHz. The Langmuir probe was placed at a fixed location (4 cm from the axis) and swept with the FSPS at 50 kHz (sufficiently above the Nyquist frequency of the spoke), obtaining a time series of plasma parameter measurements as shown in Fig. 9. Then, we applied an analysis procedure of time series data of a 4 kHz oscillatory mode in a Penning discharge using the Hilbert transform [2]. The generated phase plot using the Hilbert transform approach gives a clear picture of the average magnitude of fluctuations of the plasma parameters and their mutual phase differences for a dominant mode in an ExB discharge. This allowed for an estimation of particle transport due to azimuthal electric field fluctuations which showed that a rotating spoke contributes ≥ 1/3 of the anomalous transport in a Penning discharge undergoing spoke oscillations [2].

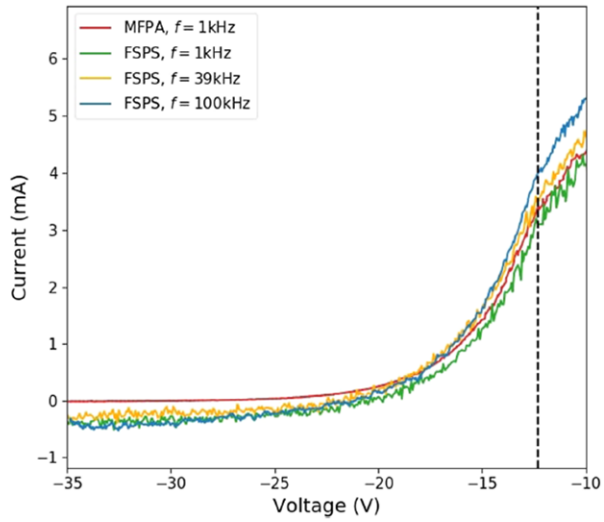

Fig. 8. I-V probe traces measured in a weakly magnetized quiescence (no spoke) plasma generated the Penning discharge operating at 1.5 mtorr xenon gas and the magnetic field of 30 Gauss. Measurements were conducted useing PPPL in-house built fast sweeping probe station (FSPS) and a commercial probe station MFPA [16]. The FSPS sweeping frequency Dashed vertical line is located at the plasma potential. Results are from Ref. [2].

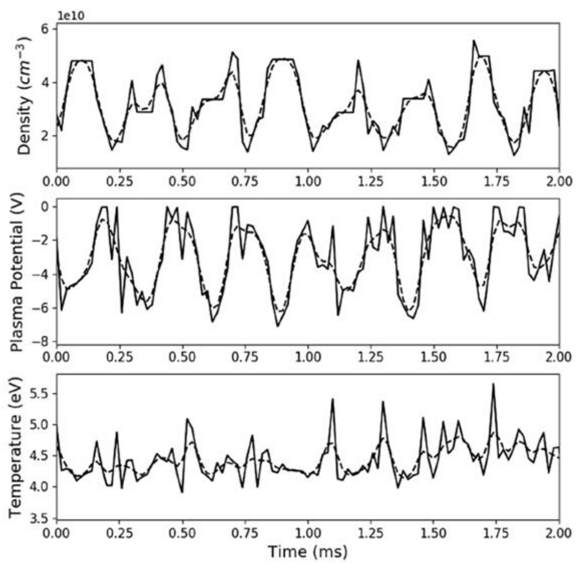

Fig 9. Time-resolving probe measurements of the plasma properties during the spoke oscillations: A sample 2 ms time series of the fast sweeping probe station (FSPS) measurements of the plasma density, plasma potential and the electron temperature. The sweeping frequency is 50 kHz. Measurements were conducted in the ExB Penning discharge at 0.1 mtorr and the magnetic field of 40 Gauss at 4 cm from the axis of the discharge. Each point is one voltage sweep. The underlying dashed curve is the result of a 2nd order lowpass Bessel filter at a cut-off frequency of 10 kHz.

IV. Conclusion

In this paper, we briefly reviewed most recent results on the use of electrostatic probes for characterization of low frequency oscillations in the ExB Penning discharge. A detail description of the probes used in these experiments, results of measurements and their analysis, including a comparison with modeling [11] and simulations [4] can be found in Refs. [1-3]. These references demonstrate that the electrostatic probes can be very useful for charaterization of transport properties in magnetized plasma such as exist in Hall thrusters. Biased and fast sweeping probes and emissive probes allowed reproducible time-reslving measurements of macroscopic plasma properties (ion density and electron temperature), electron energy probablity function and plasma potential during the spoke oscillations. Key conclusions derived from these measurements is that 1) scattering of electrons on low frequency spoke oscillations contributes significantly to the electron cross-field transport and can account for 30-100 % of the discharge current measured in the Penning discharge, and 2) by changing wall boundaries and using active biased walls it is possible to affect the spoke and the spoke-induced transport of electrons across the magnetic field. The latter may imply directions for designing of Hall thrusters with suppressed spoke activity. In this regard, it would be interesting to explore the spoke activity in already existing Hall thrusters with the metal walls (e.g. anode layer thruster and Camilla thruster).

Finally, we reported preliminary results on the effect of the magnetic field topology on the spoke activity. This topology is relevant to Hall thrusters in which the magnetic field is usually non-uniform. The measured results revealed a complex dependence of the spoke on the magnetic field – the spoke appears and disappears depending on the magnetic field magnitude. These results may imply that the ExB rotating spoke is strongly affected by gradients (e.g. magnetic field, plasma density, electric potential) in the direction along the non-uniform magnetic field [11, 23]. In this regard, it would be also interesting to consider the effect of centrifugal force on rotating electrons [24] and relevant instabilities. In any case, it is clear that to predict the observed spoke behavior and associated cross-field transport in non-uniform magnetic fields such as shown in Fig. 7, numerical simulations have to be three-dimensional that require appropriate tools (3D codes) and analysis.

Acknowledgments

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